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Investigation of Rocking Connections Designed for Damage Avoidance with High Force-to-Volume Energy Dissipation

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ABSTRACT :

Modern structures are designed with a sacrificial design principle that values life safety at the expense of energy-absorbing structural damage. The significant long term economic impact of major seismic events due to the resulting structural damage demands a new generation of structures that can withstand large earthquakes with minimal or zero damage - while guaranteeing life safety. This research presents a new approach to damage avoidance design (DAD) connections that absorb significantly more seismic energy than sacrificially designed structures. The design approach utilizes hinged or rocking connections with energy absorption provided by small volume, high force (100-400kN) lead dampers designed to fit within standard structural connections. Proof of concept experimental results are presented for three connections, including: 1) 3D exterior post-tensioned RC connection; 2) corner post-tensioned RC connection; and 3) 2D exterior steel connection. Experiments are conducted on scaled specimens which are subjected to repeated reversed cycles of seismic drifts from 0.5-4.0% in increments of 0.5-1.0%. The high force-to-volume (HF2V) dampers reliably provide over 20% more damping than other systems – and do so on every motion cycle. It is therefore concluded that this novel DAD connection can provide sustained superior energy dissipation without damage.

KEYWORDS: High force-to-volume (HF2V), Damage Avoidance Design (DAD), lead extrusion dampers, energy dissipation, precast, post-tensioned, rocking connections

1. INTRODUCTION

Earthquakes can cause significant structural damage and strength degradation, especially in beam/column connections. Current capacity design for monolithic reinforced concrete (RC) structures provides ductility by localizing inelastic behavior to specific regions called plastic hinge zones. Although damage in plastic hinge zones provides significant energy dissipation during seismic events resulting in adequate life safety, it is desirable to achieve these objectives without permanent damage. The use of a variety of emerging Damage Avoidance Design (DAD) connections utilizing energy dissipation devices enables structures to undergo inelastic hysteretic response without notable structural damage (Mander and Cheng, 1997; Solberg et al., 2008). This new design philosophy recommends precast post-tensioned rocking structures that not only protect life safety, but also reduce the financial cost related to earthquake damage.

Jointed structural connections conforming to DAD typically have low inherent damping. Recently, considerable attention has focused on yielding steel fuse-bars to provide hysteretic energy dissipation. However, emerging high force to volume (HF2V) damping devices (Rodgers et al. 2006a,b) can provide equivalent or higher forces than yielding steel fuses, and do so on every response cycle. They are also sufficiently compact to allow placement directly into structural connections. These HF2V devices use a bulged central shaft which induces a plastic flow of lead during shaft motion to provide a resistive force. The device response is repeatable on successive cycles and does not show any stiffness or strength degradation, and the devices are not subject to any low cycle fatigue issues. A schematic cross-sectional view of the device is shown in Figure 1.

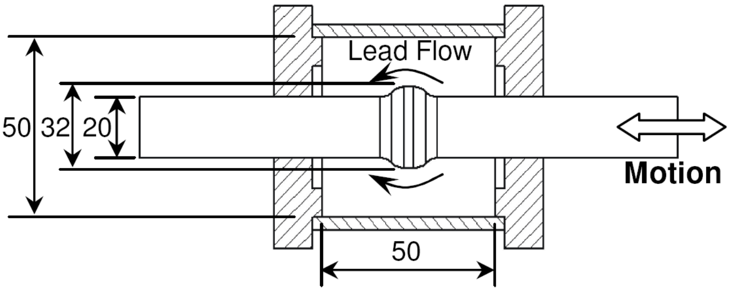


Figure 1: Cross-sectional view of the device.

This research experimentally verifies these devices in a range of DAD connections. Prototype jointed precast beam-to-column sub-assemblages and typical steel connections are tested. HF2V dampers provide the added energy dissipation with the investigation focusing on their contribution to the overall joint response.

2. EXPERIMENTAL INVESTIGATION – RC CONNECTION

The prototype ten-storey RC frame building, commonly known as the "red book" building in NZ (Bull and Brunsdon, 1998), has three 10m bays in each direction. It was designed to the New Zealand concrete standard (NZS3101: 1995) for intermediate soil. Keeping all other variables constant, the same structure was designed according to DAD principles, resulting in precast beams and columns being connected via a post-tensioning system. It also has precast floor units seated on the transverse beams, leaving the longitudinal beams to resist seismic forces.

An exterior joint of 500 kN-m moment capacity on the second floor was chosen for testing a 3D beam-column sub-assemblage. Using constant stress and strain similitude, the specimen consisting of two beams in the longitudinal direction and one beam in the transverse direction was scaled to 80% of the full size. The longitudinal and transverse beams are parts of the seismic and gravity frames and are referred to as the east-west seismic and north-south gravity beams, respectively. Figure 2 shows a photograph of the specimen and a schematic diagram of the experimental setup. An initial axial post-tensioned prestress of 400kN was provided by two 26.5mm diameter high-strength thread-bars placed in 50mm PVC ducts.

a)

b)

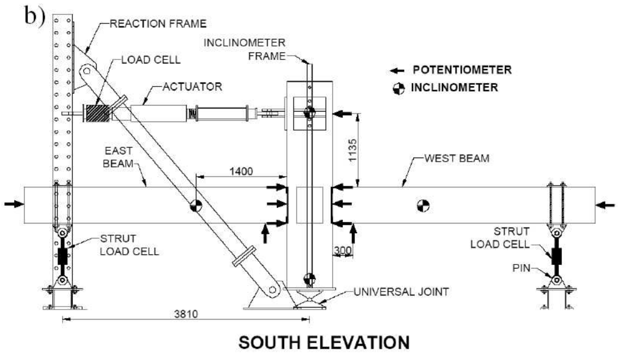


Figure 2: a) Photograph of test specimen, and b) Schematic south elevation of test setup

The tendon profile in the east-west direction utilises a straight coupler system where the tendons were pre-bent at the joint end to a radius of 1.8m. The tendons exit through the column face at the top of the beam-column interface. Straight fuse bolt-bars run at an angle through the column, with a sacrificial fuse diameter machined to 75% of the effective area to localise any inelastic tendon behaviour. A detailed schematic for the east-west connection is presented in Figure 3.

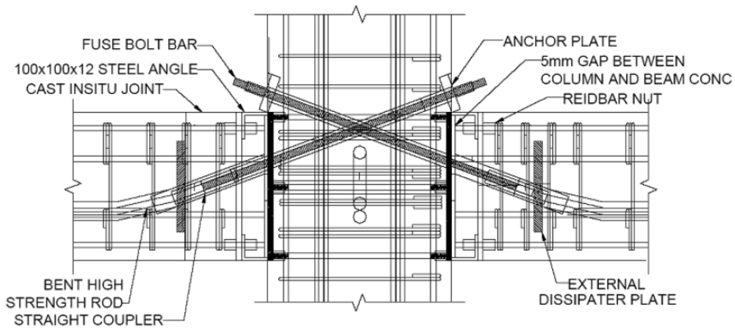
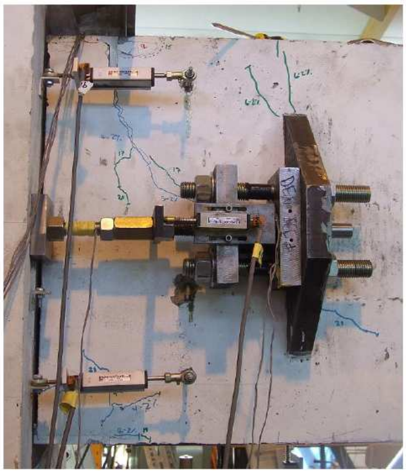


Figure 3: Post-tensioning detail at the beam-column joint in the East-West seismic direction. (Solberg, 2007)

The supplemental damping system used in the specimen included two 120kN lead-extrusion dampers mounted externally to each seismic beam, as shown in Figure 4a. Figure 4b shows the hysteresis loop for the HF2V lead extrusion dampers. To evaluate the impact of these devices only uni-direction testing in the east-west seismic direction is reported here.

a)



b)

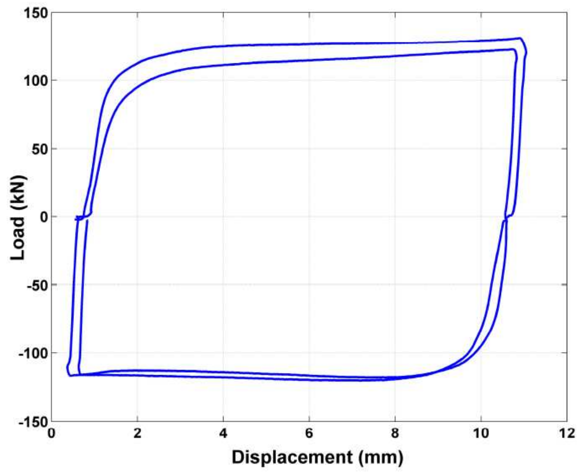


Figure 4: a) Lead extrusion damper externally mounted to the seismic beam, and b) hysteresis loop for the damper shown in a).

An additional test was also conducted by removing the east seismic beam and placing both HF2V devices on the west beam, representing a corner joint for the prototype structure to investigate the effect of doubling the contribution from the HF2V dampers. Further experimental details can be found in Solberg (2007).

3. EXPERIMENTAL INVESTIGATION – STEEL CONNECTION

Figure 5 presents the experimental setup of an exterior beam-to-column structural steel connection. The top flange of the beam was attached via an angle to the column with 4-M20 bolts, as detailed in Figure 5. Because little deformation occurred at the top of the beam, no slab tearing or damage is expected. The beam and column were made of 360UB44.7 and 310UC158 section respectively. Both members were made of Grade 300 hot rolled structural steel.

Quasi-static (QS) loading consisting of fully-reversed sinusoidal displacement cycles was used to test this beam-column joint with the HF2V devices, up to a maximum peak drift of 4%. The theoretical capacity of the lateral load applied to the column to dissipate energy is 36 kN based on the mechanics of the joint and overall moment equilibrium of the experimental setup. The devices are intended to provide all energy dissipation while the top angle acts as a hinge.

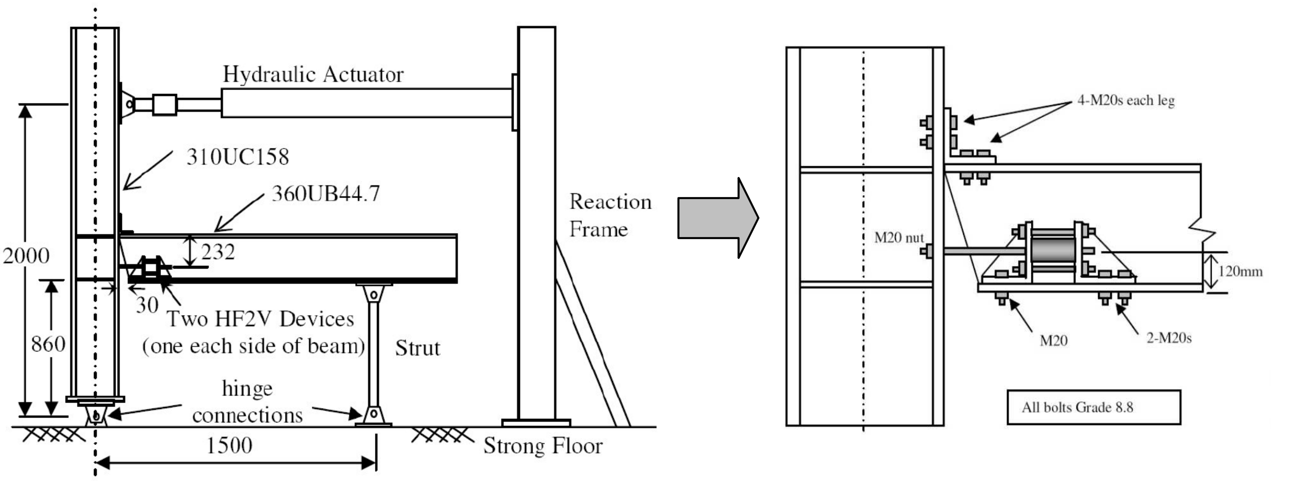


Figure 5: Experimental steel connection setup and detail of connection with HF2V device.

An important design feature is the provision of a 30mm movement gap between the column face and bottom beam flange, as shown in Figure 5. The beam was cut back at an angle of approximately 8% to prevent the bottom flange from damaging the column under joint-closing up to 4% drift, enabling free, hinged motion. Two HF2V devices were used, with one on either side of the beam web. Displacement controlled QS tests were performed using a hydraulic actuator attached to the column, 2m above a hinge connection to the strong floor.

Column top displacement was measured with an external rotary potentiometer. Load cells connected to the damper shafts measured the forces in the HF2V devices, while potentiometers measured the in-service damper displacement. Other linear potentiometers were placed to capture potential losses of stiffness and undesired movement in the subassembly, particularly due to device bracket compliance.

4. EXPERIMENTAL TEST RESULTS AND DISCUSSION

4.1. Exterior Joint Results

The exterior RC joint specimen was subjected to uni-directional displacement cycles of fully reversed sine wave profile. The test was displacement-controlled and the displacement cycles were gradually increased to induce story drifts of 0.25%, 0.5%, 1%, 2% and 3%, and two fully reversed cycles at each drift level. The column shear force vs applied drift response obtained from this test is presented in Figure 6a. At 0.25% drift, the joint remained closed, as only elastic column deflection occurred at this loading stage. Minimal joint opening was observed at the 0.5% drift cycles, with notable joint opening at the 1% and 2% cycles. Due to flexibility in the connection to the strong floor, the column base pin support moved slightly; thereby resulting in an apparent lack of perfect recentring near the origin. This small non-zero residual displacement would not have occurred if the pin support was rigidly attached to the strong floor.

As indicated by narrow hysteresis loops in Figure 6a, the design force of 120kN for the lead extrusion dampers was a conservative choice from a design standpoint. The key motivation was to maintain a large factor of safety against the loss of overall joint recentring. If the resistive force provided by the dampers exceeds the post-tensioning force then the joint could be at risk of losing the ability to self-centre following an earthquake.

4.2. Corner Joint Results

After performing numerous tests on the initial test specimen, the east beam was removed, and both dampers were placed on the west beam to double the damping force. This new setup represents a corner joint of the building, and testing with this setup allows the recentring limit to be experimentally investigated. It is important to note that a breach of the recentring limit represents the requirement of an external force to re-centre the joint, and is shown in a hysteresis loop by a zero-force crossing of the horizontal axis at a non-zero displacement value.

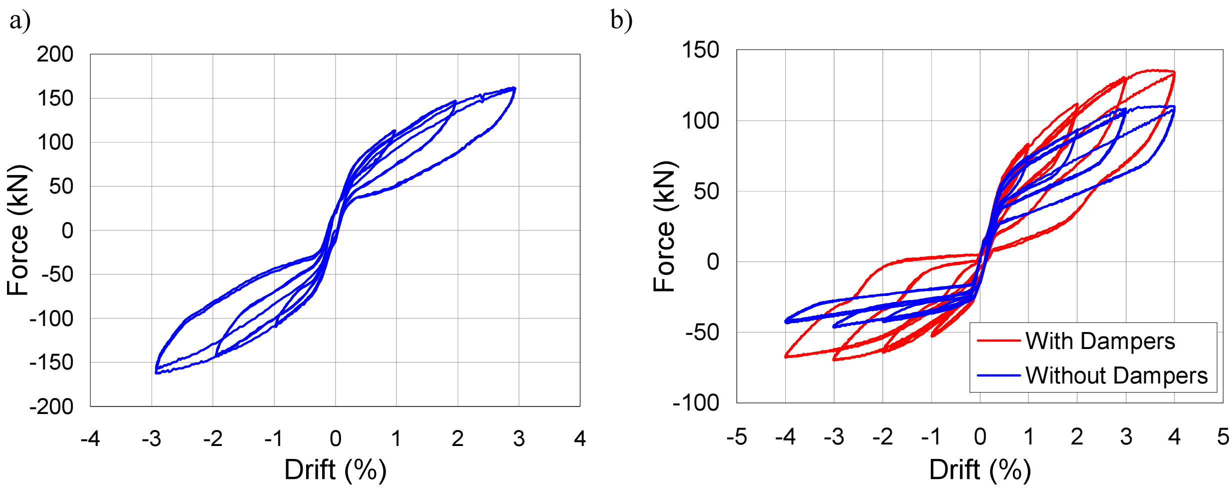


Figure 6: a) Experimental results for the 3D exterior joint, and b) Comparison of hysteresis response of the corner joint with and without dampers.

Furthermore, it was of particular interest in this comparison to investigate the contribution that the supplemental damping system made to the overall joint hysteresis. Therefore, testing was performed on the joint with and without the dampers. Testing was again limited to uni-directional displacement inputs for these configurations as no damping system was applied to the north-south gravity beam. The peak drift corresponding to the displacement inputs was increased to 4%, but two fully reversed cycles at each drift level were used to investigate the effect of repeated cycles on any inelastic tendon behaviour. Experimental load-displacement curves up to 4% drift are presented in Figure 6b.

The first notable observation is that the hysteresis loop is asymmetric. This phenomenon can be attributed to the fact that the post-tensioning tendon arrangement has the tendons eccentrically placed relative to the beam centerline at the beam-column interface, as shown in Figure 3. Although this eccentricity has always been present, the loops presented in Figure 6a do not show this asymmetry, as the presence of both the east and west beams balanced out this effect. Although the forces at each interface were asymmetrical, the west interface was undergoing the opposite joint rotation to that of the east interface, resulting in overall symmetry of the hysteresis loops. The removal of the east beam removed this cancellation, resulting in the asymmetric force-displacement loops of Figure 6b.

As expected, the overall joint hysteresis loops are substantially larger when the dampers are present. Interestingly, the area enclosed within the hysteresis loops for the joint without dampers shows large disparity between the two directions. Again, this phenomenon can be traced back to the tendon profile. The inherent hysteresis for the joint without dampers is related primarily to the friction between the prestressing tendons and the PVC duct in which they are contained. The bent tendon arrangement results in notable friction between the tendon and PVC duct as the tendon undergoes deformation from gap opening. The curve of the tendon naturally results in higher friction for gap-opening in one direction than the other.

Another important observation is the loss of recentring ability of the joint at 4% drift, as seen by the crossing of the horizontal axis at a non-zero displacement. Although the recentring capability is lost, it is only lost for negative drift angles at the largest expected (failure) drift of 4%. Importantly, the external force required to re-center the joint was a relatively minimal 5 kN, indicating that using this level of damping is slightly beyond the upper limit to be incorporated in design if very large drifts are expected.

Figure 6b also indicates that the effect of the connecting rod and damper mount flexibility has a notable effect on the overall hysteretic response. At peak drift, the connecting rods to the dampers are in a state of elastic tension due to the load they are carrying. Immediately after the peak drift the connecting rods must undergo a period of reduction in elastic tension before undergoing elastic compression when the damper can again dissipate energy. The effects of this flexibility can be clearly seen in Figure 6b, where due to this elastic deformation of the connecting rods and mounting plates, localized flattening of the hysteresis loops can be observed during unloading. These factors slightly reduce the effectiveness of the dampers, and designers would be advised to use as stiff as practicable connecting rods and mounting plates.

Despite the aforementioned consequences of the flexibility of the damper mounts and connecting rods, significant increase in absorbed hysteretic energy is achieved when compared to the joint without dampers. In particular, for the 4% drift cycles in the negative drift direction, the enclosed hysteretic energy with the dampers is over 400% of the hysteretic area of the joint itself, indicating a 300% increase in absorbed energy, with only minimal effects on the ability of the joint to statically re-centre.

4.3. Steel Joint Results

Two fully reversed lateral displacement cycles were applied to the structural steel beam-to-column joint at drift amplitudes of 0.5%, 1%, 2%, and 3% and four cycles at 4%. The resulting experimentally observed joint hysteresis is presented in Figure 7a. It should be emphasized that under cyclic loading for a given drift amplitude the hysteresis loops are stable. No strength degradation was observed, which is common in other structural materials such as reinforced concrete and welded steel connections. In addition, energy dissipation is equal in repeated fully reversed cycles at each drift level, even when these cycles were separated by larger or smaller drift cycles. This phenomenon is unique to this type of DAD connection and would not occur in conventional connections or in DAD connections with sacrificial fuse bars.

Figure 7a also plots the theoretical lateral strength capacity of 36kN. The strength capacity is based on a total connection force of approximately 150kN. Note that because of the mild velocity dependence, the observed strength tends to exceed this limit at high drifts when the cyclic loading rate correspondingly increased. This effect is shown in Figure 7b, where the in-joint measured damper force is plotted against the “in service” device movement. The slight increase in force for larger drifts is evident, and is due to a test procedure that moved the column to each drift in a fixed time period for all drift sizes; thereby increasing the velocity as the drift size increased.

The experimental yield drift was approximately 1%. This result is higher than the expected value of 0.5% calculated based on elastic deformation of the column, beam, strut and HF2V device shaft. This increase in elastic motion is likely due to the additional flexibility of the damper (angle) mounts and the in-series load cells connected to the HF2V devices. Instrumentation measured negligible movement vertically or horizontally in the top angle, confirming the rigid, hinged nature assumed.

Figure 7a shows the column force versus lateral drift relationship for the subassembly of Figure 5, when slip deformation of the mounts is prevented. It may be seen that the stiffness at low force levels in quadrants 2 and 4 is less than in quadrants 1 and 3. This difference is attributed to the rocking-like flexibility introduced into the system by the HF2V device mounting brackets. This conclusion is supported by the plot in Figure 7b where the device itself exhibits approximately a rigid perfectly plastic performance. Hence, the difference between the responses of the device itself and its contribution to the total assembly is due to compliance in the device connections.

At 0.5% drift amplitude there was little movement (approximately ±0.2mm) in the device. This small motion resulted in negligible energy dissipation, as seen in Figure 7a. As the lateral load increased the bulge began to move more significantly and much more energy was dissipated. Virtually all energy dissipated can be attributed to the device, as there was no yielding of the principal structural elements in the experiment.

It should be noted that there was a slightly larger displacement in the device when the beam-column gap opened, compared to when it was closing. Noticeable elongation was observed in the bolts connecting the damper shaft to the column face when the joint was fully open, contributing to this difference.

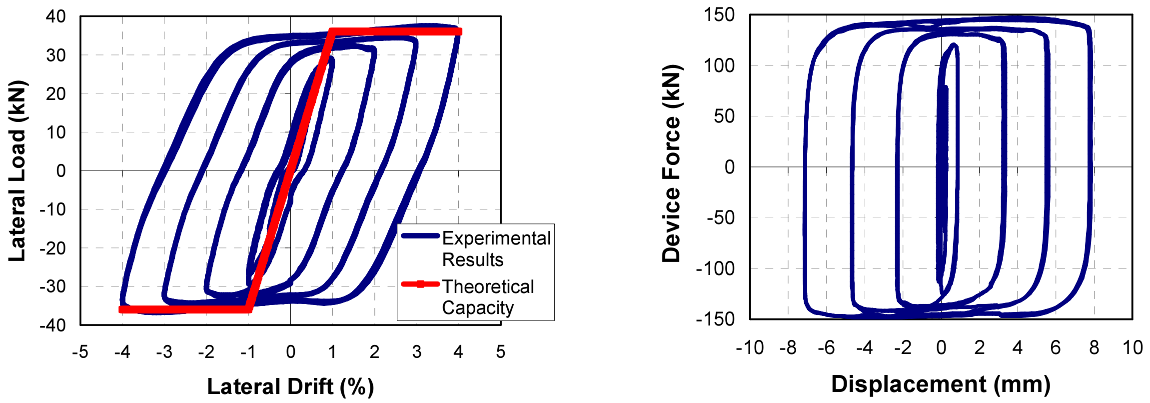


Figure 7: a) Lateral load versus drift hysteretic performance of the subassembly; and b) Force-displacement response of the in-service device.

The physical gap of 30mm between the column face and bottom beam flange provided adequate space for rotational movement without damaging either element. This approach is realistic as a flush connection would cause undue damage to either element and prevent the device from moving and dissipating energy. The overall design approach is thus one of a hinge with a separate dissipater.

Energy dissipation efficiency may be computed as the ratio of the energy dissipated in one cycle of the subassembly to that of an elastic perfectly plastic loop with the same initial stiffness as the device. As shown in Figure 8, the devices provide an 80% efficient dissipation at 3% drift. In contrast, based on the work of Pekcan et al. (1999) and Shama et al. (2002), a standard rigid steel connection that will suffer permanent damage, is only about 60% efficient on 3% drift cycle, and the efficiency further reduces on subsequent larger drift cycles. On the other hand, the tested DAD steel joint was completely undamaged after the 4% drift cycles had been applied.

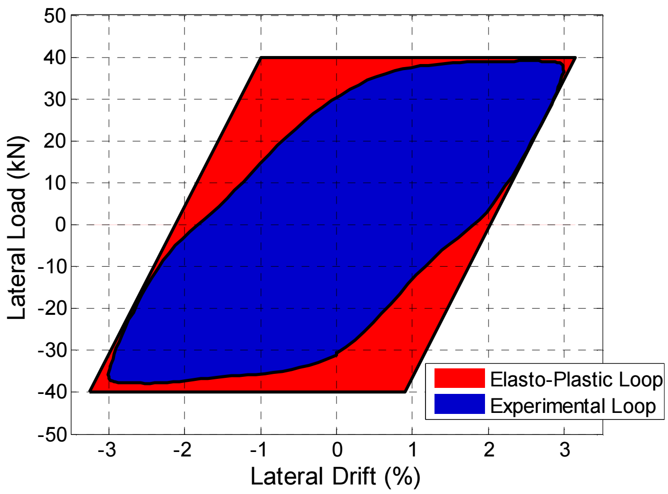


Figure 8: Energy efficiency factor of 80% for the DAD connection compared to the equivalent elasto-plastic hysteresis loop

5. CONCLUSIONS

This study has presented a proof-of-concept experimental investigation of lead extrusion based HF2V energy dissipation devices fitted directly into RC and steel DAD connections. Based on the results, the following conclusions can be drawn:

1. It was demonstrated that the HF2V devices provide a level of energy dissipation comparable to, or in excess of, mild steel devices designed for the same yield force at low drifts. Larger drifts resulted in significantly increased energy dissipation from the extrusion dampers. Subsequent smaller motions also received full dissipation, which would not occur with yielding dissipaters. No damage was observed to the main structural beam and column elements in any test.
2. HF2V devices offer high force and do not suffer from low-cycle fatigue that other devices such as yielding steel fuse bars exhibit. The force in the devices creeps back towards zero upon unloading, and they thus provide an increased ability for the structure to self-centre and need no maintenance following an earthquake.
3. The overall design approach is generalizable, and the HF2V damping devices can be configured in several ways around the connection to accommodate any other constraints, and are shown to be equally applicable to both steel and reinforced concrete connections.

The overall outcome complies with the general tenets of Damage Avoidance Design (DAD) and represents a significant way forward for these types of connection. In particular, the results indicate the feasibility of this novel high force-to-volume (HF2V) damper in realistic structural connections.

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